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Comprehensive Review of Mobile Ad Hoc Networks (MANETs): Routing Protocols, Applications, and Challenges

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***Abstract*—**A Mobile Ad Hoc Network (MANET) is a group of two or more devices (called nodes or terminals) that can communicate wirelessly without the need for a central administrator. These devices can create a network on their own and exchange information without relying on any fixed network infrastructure. In this system, mobile devices connect using wireless links, and they can move freely. Sometimes, they also act as routers to help pass information through the network. This paper explains how MANETs are different from traditional wired networks. Unlike wired networks, the structure of a MANET can change at any time because there are no fixed connections, and the devices can move in any direction. This creates a need for a new type of routing protocol to find the best path for communication between nodes. An ideal routing protocol for MANETs should be able to find the right path and quickly adapt to changes in the network.

The paper also covers the history of ad hoc networks, wireless ad hoc networks, mobile approaches, and the different types of MANETs. It also discusses over 13 types of routing protocols for MANETs, analyzing their key features, advantages, and disadvantages. Finally, the paper explores the applications and potential services of ad hoc networks in detail.

Keywords*— *Mobile Ad Hoc Networks, Wireless Communication, Routing Protocols, Dynamic Topology, Infrastructure-less Networks.

I. Introduction

As wireless communication and computers have grown rapidly, mobile computing has emerged as a crucial component of computer communication. Comprising connected devices, or "nodes," that dynamically create the network, a Mobile Ad Hoc Network (MANET) is a fully wireless network. These networks frequently feature varying bandwidth and a dynamic structure. Mobile phones, PDAs (Personal Digital Assistants), digital cameras, MP3 players, computers, and more can all be considered network devices.
When devices move between locations while maintaining the same IP address, this is referred to as "mobility" on the Internet. Mobile IP technology, which manages IP addresses and routes data via Home Agents and Foreign Agents, makes this feasible. It is comparable to fixed networks because of this.

On the other hand, mobility in a MANET is entirely wireless and does not necessitate any fixed infrastructure, such as a base station. Unlike mobile IP, every device in the network has unrestricted access and can function as both a user and a router.

Early military mobile packet radio networks served as the model for MANETs, and technological developments have reduced the size, weight, and power consumption of communication devices. As the idea of Personal Communication Systems (PCS) developed, mobile phones became a vital component of modern life, enabling us to communicate at any time and from any location.
MANETs are essential for unit-to-unit communication in the military, since field hazards may prevent the availability of fundamental communication infrastructure like base stations. Like this, MANETs' completely wireless and movable nature makes them ideal for situations where infrastructure cannot be depended upon, such as mountain rescues, maritime operations, or disaster relief.
As personal communication devices become more sophisticated, MANETs may also be helpful in group settings where a lot of data needs to be shared. To effectively transfer files or execute applications, for instance, temporary networks can be set up without the need for permanent hardware like cables.

Bluetooth technology is an excellent illustration of how wireless devices can connect to one another. If Bluetooth designs incorporate MANETs, additional options may become available.

II. Background

Nowadays, wireless technology is used in the majority of information technology. One drawback of traditional mobile and cellular networks is that they still require infrastructure, such as base stations and routers. On the other hand, this restriction is eliminated via Mobile Ad Hoc Networks (MANETs). The evolution of wireless networks depends on MANETs. They are composed of identical devices, also known as nodes, that interact with one another over wireless networks devoid of centralized management. Despite being developed initially for military communication, MANETs are increasingly being used in other fields. Rescue efforts during natural catastrophes, law enforcement activities, and commercial applications such as sensor networks are a few examples. Our everyday lives are now significantly impacted by MANETs, and their applications are only growing.

Ad Hoc Networking is a well-established concept. Its origins can be found in the 1972 DARPA Packet Radio Networking (PRNET) project [1,2,3], which evolved into the Survivable Adaptive Radio Networks (SURAN) initiative [4]. The effectiveness of packet-switching technologies, such as bandwidth sharing and store-and-forward routing, served as the impetus for these efforts. Mobile Ad Hoc Network environments were found to benefit from these technologies. Although they were mobile at the time, hardware such as routers and repeaters for packet radio networking systems had very little mobility. Nevertheless, for the time, the protocols created in the 1970s were seen as sophisticated. The ability to integrate all nodes and network devices into a single unit—known as Ad Hoc Nodes—was later made possible by developments in microelectronics technology. Ad Hoc networks are now very helpful for military operations because of the advantages they have brought about, including flexibility, resilience, mobility, and independence from fixed infrastructure. Their deployment on the battlefield was swiftly accepted. In military applications and related research initiatives like the Near-Term Digital Radio (NTDR) program and the Global Mobile Information Systems (GloMo) program [5], ad hoc networks have been crucial [6]. Their application has grown over time to include business sectors, police operations, and rescue missions in unstructured or chaotic settings.

Ad Hoc Networks research was mostly centered on military applications for a long time. The advantages of Mobile Ad Hoc Networks (MANETs) outside of the military became apparent in the mid-1990s as wireless communication and commercial radio technologies advanced. At the Internet Engineering Task Force (IETF) conference in 1995 [7], the topic of Ad Hoc Networks was first discussed. By 1996, the emphasis was on Mobile Ad Hoc Networks, specifically in wearable computer networks, tactical networks, and military satellite networks. How to modify current routing techniques to accommodate IP networks in dynamic contexts was the topic of discussion.

To address these issues, the IETF established the Mobile Ad Hoc Network Working Group (MANETWG). Although many of the current solutions were made for tiny networks with a few hundred nodes, MANET development also depended on pre-existing IETF standards, such as IP addressing and Mobile IP.

Research on MANETs is already a vibrant and expanding subject. Alongside new and emerging radio technologies, it is developing. The Ad Hoc Wireless Network and Computing Consortium was established recently to coordinate industrial and academic efforts to use this technology in a variety of fields. This covers the use of MANETs for remote networking, peer-to-peer communication, and home wireless networks.

These initiatives are opening the door for new and innovative applications in a variety of disciplines as well as commercially viable MANETs. Pervasive (widespread) computing environments are becoming more prevalent as communication and computing technologies continue to develop. Both conventional infrastructure-based wireless networks and cutting-edge infrastructure-less MANETs will be a part of the next generation of mobile communication.

III. Peer-To-Peer Wireless Networks

A Mobile Ad Hoc Network, or MANET, is a collection of two or more wirelessly communicative devices (referred to as nodes or terminals) that do not require a central system or fixed infrastructure such as routers. These wireless gadgets have the ability to autonomously join networks and exchange data. MANETs are self-organizing networks with mobile devices (nodes) that can function as routers and users. Because devices can join or leave the network at any time, the topology (or layout) of the network is always changing. Because of this, MANETs are extremely adaptable but also difficult to administer [8]. Without any central authority, all devices in MANETs are in charge of self-organization and managing functions including routing, network administration, and maintenance. Peer-level multi-hopping is a technique that enables data to move amongst several devices before arriving at its final destination. Ad Hoc networks are built on this property, which also makes them more complicated than conventional wireless networks.

MANETs frequently group (cluster) devices to manage this complexity more effectively. Devices in an Ad Hoc Network are connected as seen in the accompanying diagram (diagram 1), with some moving at varying rates and directions. People's living spaces in the future will be dependent on data from interconnected communication networks. Since wireless devices are now generally accessible and reasonably priced, mobile computing has expanded quickly. In addition to more conventional home appliances like digital cameras, ovens, washing machines,

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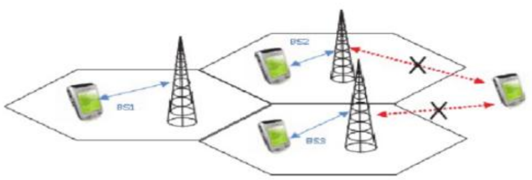
refrigerators, and thermostats, new compact gadgets like mobile phones, laptops, PDAs, and handhelds are now being outfitted with computer and communication capabilities. As a result of this expansion, technology is now more pervasive and incorporated into daily life. New pervasive computing standards, including updated tools, services, devices, protocols, and architectures, are required to support this. Ad Hoc network users also profit from their own advantages. Because these networks don't require wiring or physical connections, they save money and space. They are effective, user-friendly, and compatible with smartphones and other mobile devices. Wireless networks are perfect for mobile and local wireless communication since they are especially helpful for local area connections.

The use of technology has increased in recent years. Information shared through connections between various communication networks is transforming how people will live in the future. The proliferation of widely accessible and reasonably priced wireless devices has also led to a rapid expansion in the field of mobile computing. Mobile phones, laptops, PDAs, and handheld devices are examples of new compact electronics that are becoming more and more common. Digital cameras, cooking ovens, washing machines, refrigerators, and thermostats are just a few



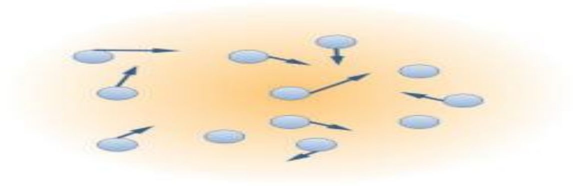
examples of conventional home appliances that now have communication and processing capabilities. This field is growing to be completely pervasive and incorporated into everyday life. To facilitate this, technologies need to create a more modern and improved system for pervasive computing, which includes new devices, protocols, architectures, tools, and services.

Because ad hoc networks do not require a fixed connection or wiring, people and internet users today benefit greatly from them. Space is saved, expenses are reduced, and usability is enhanced. They work with mobile phones as well. Local wireless network configurations are simple to utilize as a result of these advantages. Additionally, local area network terminals can benefit from wireless networks [9].

IV. STRATEGIES FOR MOBILE WIRELESS SYSTEMS

Over the last ten years, mobile networks have emerged as one of the key technologies for enabling and expanding access to computing. The prevalence and variety of mobile devices and wireless networks have increased due to advancements in both software and hardware.

We will now discuss the two main ways that IEEE 802.11, or mobile wireless networks, can connect [10,11]. There are two types of wireless networks: infrastructure and infrastructureless (also known as ad hoc) networks. We'll go over each of them below.



A. Wireless Networks with Well-Established Frameworks

In this configuration, a fixed third-party device known as a Base Station allows wireless devices to interact with one another, as illustrated in Figure 2. Radio resource usage is controlled by the Base Station, which also handles device-to-device transmission.

A source device notifies the Base Station when it want to transmit data to a destination device. The path between the devices is not necessary for them to know. Just that the source and destination devices have to be within range of the Base Station. Communication will either fail or cease if either device is out of range.

B. Wireless Ad Hoc Networks

An Ad Hoc Network (MANET), another name for a mobile wireless network, is a collection of two or more wirelessly communicative devices or nodes. Neither a fixed network infrastructure nor a central administrator are required for these devices to speak with one another directly. To exchange data, the wireless nodes can organize into a network on their own. When necessary, they can even take on the role of routers [12,13]. Wireless links are used to connect mobile devices to this kind of autonomous, dynamic network. An essential strategy in communication technology that enables fully ubiquitous computing is infrastructureless networks. This is due to the fact that mobile devices frequently need to communicate with one another without

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depending on a fixed network. Rapid advancements in wireless communication are being made to meet this demand.

One basic example of how Ad Hoc networks operate is depicted in Figure 3.

This figure illustrates the operation of Ad Hoc networks. There are three nodes in the example: (S), (A), and (L). Although they are out of each other's transmission range, the source node (S) and the destination node (L) wish to communicate. They transfer data from one node to the other using the intermediary node (A) to send and receive packets. The node (R) serves as both a host and a router simultaneously. An apparatus that determines the route a packet should travel to get to its destination is called a router. The router chooses which node to deliver the packet to next based on its current knowledge of the network, guaranteeing that it eventually reaches its destination.

V. Categories of Ad Hoc networks

There are two primary categories of Wireless Ad Hoc Networks: The nodes in quasi-static ad hoc networks can be either fixed or mobile. However, the network structure could vary often due to link failures and power control problems. A Sensor Network is an excellent illustration of this kind [14]. The entire network is mobile in mobile ad hoc networks (MANETs), and nodes can move rapidly about one another. We will now go into greater depth about both kinds.

A. Network of Mobile Wireless (MANET)

A collection of separate mobile devices connected by wireless networks is known as a mobile ad hoc network, or MANET. The network structure varies with time, and its bandwidth is constrained. Additionally, each gadget serves as a router, facilitating data transmission between devices. This network can function alone or as a component of a LAN, which is a bigger network. Three varieties of MANET exist:

- Ad hoc Networks for Vehicles (VANETs)
- Ad hoc networks for intelligent vehicles (InVANETs)
- Mobile Adhoc Networks Based on the Internet (iMANET)

MANETs can be anything from big, dynamic networks to tiny, low-power networks. It is difficult to design protocols for these networks. For routing, link scheduling, and network administration, MANETs require efficient distributed algorithms. Because the network structure can change at any time, standard routing techniques are ineffective in this setting. We require specific routing algorithms for MANETs that take into account the dynamic nature of the network. Although on a fixed network, the shortest path is typically the optimal one, MANETs are not always a good fit for this strategy. The quality of wireless links, interference, energy consumption, and network fluctuations are important routing concerns. This is especially crucial in military settings where routing issues need to be resolved while maintaining

security, low latency, dependability, jamming protection, and failure recovery. The performance and dependability of the network may decrease if any of these requirements are not satisfied.

B. Network of Mobile Ad Hoc Sensors

When opposed to standard sensor networks, which typically connect with a central controller, a mobile ad-hoc sensor network operates more freely and is simpler to build. A hybrid ad hoc network, sometimes known as a mobile ad hoc sensor network, is made up of numerous sensors dispersed over a vast region. In addition to having some intelligence to process signals and transmit data, each sensor may manage mobile communication. Through the routing protocol, mobile devices can communicate with each other by determining which devices are connected and sending data appropriately. Mobile ad hoc sensor networks are appropriate for practically any situation because of their adaptability [15]. Researchers are increasingly using wireless ad hoc sensor networks [16].

This is due to the fact that these networks' characteristics were previously poorly understood and disorganized. Among this network's advantages are:

- Capacity to establish extensive networks Using sophisticated procedures.
- Decreased communication requirements through dispersed or local task execution Power-saving capabilities based on network and environmental circumstances
- The usage of wireless sensor networks in practical applications is growing as a result of developments in sensor network technology.

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For instance, updating outdated fire detection systems in woods might shorten the detection time. Large buildings that currently employ intricate wired systems to monitor the surroundings provide another example. Each device in a mobile ad hoc sensor network may have a variety of sensors to identify local occurrences. Ad hoc sensor networks are also easier and less expensive to set up and maintain [16,17,18].

VI. Types of Traffic in Ad Hoc Networks

Ad Hoc networks and infrastructure wireless networks handle different kinds of traffic. Now let's examine these types:

- Peer-to-peer (P2P) communication is the exchange of information within a single hop between two devices that are near one another. In most cases, network traffic (measured in bits per second) is steady and constant [19].
- Remote to Remote refers to communication between two devices that are connected steadily but are not within one hop of one another. This may occur if several gadgets move or remain in close proximity to one another. It moves similarly to normal network traffic.
- Device movement results in dynamic traffic, which modifies network routing. This results in intermittent network activity and poor connectivity.

An IEEE 802.11 network, for instance, has two different sorts of structures: Ad Hoc Wireless LAN and Infrastructure Wireless LAN.

A. *Wireless local area network infrastructure*

As illustrated in Figure 4, this sort of network includes an access point. Its function is to connect one or more wireless local area networks (WLANs) to existing wired network systems, allowing WLAN stations to communicate with other devices. This network is notable for its fixed, well-placed base station, consistent network configuration, and dependable connectivity. The base station is meticulously planned, ensuring a safe atmosphere and a reliable connection [20]

B. *Ad Hoc Wireless LAN.*

This form of network does not rely on established infrastructure, therefore it is a wireless local area network (LAN) in which devices can communicate directly with one another within a given area. The devices may or may not interact with the outside world. In this configuration, one or two people can communicate directly, and the network includes at least two or more devices. It differs from other networks in that there are no fixed base stations. The network evolves quickly, and its structure can be influenced by interference. The devices automatically build the network with no fixed infrastructure and adapt to changes in the network configuration. Figure 4 illustrates the Ad Hoc Wireless network.

VII. Different Types of Ad Hoc Protocols

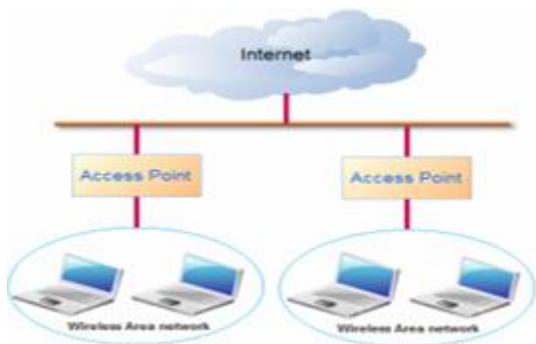
According to the IETF RFC 2501, MANETs have the following properties.

- Dynamic topologies allow nodes (devices) to roam freely, causing the network configuration to change rapidly. The network can also support both symmetric and asymmetric connections.
- Bandwidth-Constrained & Variable Capacity Links: Wireless links, unlike wired networks, have a smaller capacity and are susceptible to external influences such as noise, interference, and signal deterioration.
- Energy-Constrained Operation: Because devices such as laptops and mobile computers are powered by batteries, regulating energy use to avoid battery depletion is a significant factor in system design.
- Limited Physical Security: As networks become more integrated into our daily lives, ensuring security in wireless networks has become a top priority.

Ad Hoc network routing protocols are classified into three groups based on how they implement routing [21,22,23,24,25,26,27].

A. *Table-driven Routing (Proactive)*

This style of routing updates the route information at regular intervals. Wireless nodes frequently communicate information about available paths and update their route tables depending on the most recent data. If the network topology changes (e.g., a path becomes invalid or a new path is created), all nodes are



updated with the new path information.

Routes are stored in the nodes' routing tables so that they are readily available when needed. However, this strategy necessitates periodic broadcasts of changes, which might squander wireless bandwidth and battery life. To reduce bandwidth, the time interval between broadcasts can be increased; however, this may make route tables less accurate and slow to reflect network changes.

B. On-Demand Routing (Reactive).

This sort of routing generates routes only when they are required to transmit data. When a wireless node wishes to communicate data to another node, it initiates a "path discovery process" that locates and stores the route in a register. The route is valid until it expires or a problem arises. This strategy uses less bandwidth since the nodes do not have to constantly save information about the entire network. The main benefit is lower bandwidth utilization, but the disadvantage is that determining a route can take longer. This might create delays, increasing the average time to transfer data [28].

C. Hybrid.

This style of routing combines the advantages of proactive and reactive protocols. It may also leverage additional tools, such as GPS, to accelerate route searches and data transmission [29, 30]. There are over 13 different types of routing protocols, however we will focus on the most used ones. We'll talk about how each one operates and compare the differences.

Comparison of Proactive, Reactive, Clustered, and Hierarchical Routing

Proactive Versus Reactive Approaches

Ad hoc routing protocols are classified into two types based on their operation: proactive (table-driven) and reactive (on-demand) [31]. Proactive protocols require all nodes in the network to maintain routes to all destinations. This ensures that when a packet needs to be sent, the route is already open and ready for use.

When the network topology changes, updates are distributed throughout the network. Examples are "destination-sequenced distance-vector" (DSDV) [32], "wireless routing protocol" (WRP) [33], "global state routing" (GSR) [34], and "fisheye state routing" (FSR) [35]. These methods reduce new communication delays, but they require additional bandwidth to keep routing information up to current. Reactive protocols (On-Demand) establish routes as needed. If a node wishes to communicate data but does not know the route to the destination, it initiates a "route discovery process" to locate it. Once located, the route is followed until it is no longer required or the goal becomes inaccessible. Examples are "ad hoc on-demand distance vector routing" (AODV) [36], "dynamic source routing" (DSR) [37], and "cluster-based routing protocol" (CBRP) [38]. Reactive protocols consume less bandwidth since they do not require regular route updates, yet selecting a route takes time, resulting in delays.

Proactive protocols offer low delay when initiating new communication, but they consume more bandwidth owing to frequent updates. Reactive protocols require less bandwidth but may take longer to build routes. Reactive protocols might potentially generate unneeded traffic if route discovery is required frequently. In the following sections, we will go over each protocol in depth and explain how they work.

Clustering & Hierarchical Routing

Scalability is a significant difficulty in ad hoc networks. Scalability refers to the network's ability to deliver good service even with a huge number of nodes.

- Proactive protocols emit more topology control messages as the number of nodes rises. These messages accumulate quickly and can consume a significant amount of network capacity.

- In reactive protocols, excessive route requests can cause "broadcast storms" (excessive traffic) on the network.

When a network grows too large, the storage and computing routing needs become insurmountable. If the nodes are movable, the frequent routing updates exacerbate scalability issues. To address these issues, hierarchical routing is used.

1. Hierarchical routing divides nodes into groups (clusters) and distributes distinct tasks to nodes within and outside of each group.

2. This minimizes the size of the routing tables and update messages by focusing solely on a small portion of the network.

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3. Limiting the broadcast range of route requests can help reactive protocols run more efficiently.

The ideal technique to create a hierarchy is to group close nodes into clusters. Each cluster has a "cluster head" who communicates with the other nodes and clusters. One example of hierarchical routing is the Zone Routing Protocol (ZRP) [39].

VIII. EXISTING AD-HOC PROTOCOLS

There are about 13 different routing systems for ad hoc networks. Some of the most representative protocols are discussed and contrasted here to help readers better understand existing Ad Hoc network technologies [40].

A. *Destination Sequenced Distance Vector Routing (DSDV):* DSDV [32, 41] is an upgraded version of the standard Bellman-Ford routing algorithm designed for Ad Hoc networks. It is a table-based protocol that states. Each node keeps a routing database that contains all possible routes to other nodes, the number of hops required to reach them, and a sequence number to avoid obsolete paths.

The sequence number helps keep the routing database up to date and prevents loops. If the network topology does not change much, only minor changes (called "incremental packets") are shared. If there are many changes, the whole routing table is exchanged (known as "full dump packets"). DSDV is ideal for dynamic networks such as MANETs since it only updates when necessary and avoids superfluous data exchanges.

B. *Global State Routing (GSR):* GSR [35] enhances DSDV by minimizing routing message flooding. Each node stores the following:

- Neighbour List: This list contains all of the surrounding nodes with whom it can connect directly.
- Topology Table: Stores connection status information for each destination, together with timestamps. The Next Hop Table specifies the next hop for packets sent to each destination.
- Distance Table: Shows the shortest distance between each destination node. When a link changes, the node generates a routing message.

If the message contains a newer sequence number than what is stored, the node updates its topology database, reconstructs the routing table, and broadcasts the information to its neighbors.

C. *Cluster Head Gateway Switch Routing (CGSR):* CGSR [42] extends DSDV by using a cluster-based structure. Nodes are organized into clusters. Each cluster has a cluster leader who manages the nodes in its group. Cluster heads communicate with one another through gateways, resulting in a hierarchical structure. Links within clusters or between cluster heads are routed using DSDV. Each node maintains a routing table that records the pathways to all other nodes, as well as information about the cluster heads. This clustering method increases network organization and scalability while maintaining DSDV routing principles.

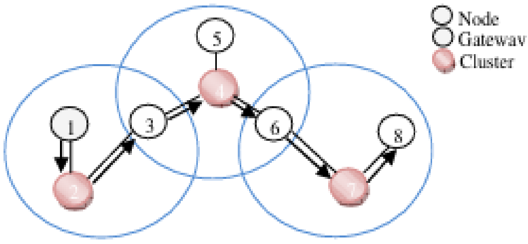

Fig 5. CGSR: Routing from Node 1 to Node 8.

Finally, in real CGSR networks, selecting which nodes should be picked as cluster heads, how to handle cluster head movement, and how to avoid major changes in the path when a new cluster head is required are all difficult tasks.

11.4 Wireless Routing Protocol (WRP) [43] use a routing database at each node to perform routing. Unlike DSDV and CGSR, each node in WRP must keep four tables: Distance, Routing, and Link Cost.

- WRP updates the Message Retransmission List Table between nodes to maintain their link relationship.
- The Message Retransmission List (MRL) keeps track of which messages should be reissued and which need to be confirmed.
- WRP employs distance and second-to-last hop information to identify the optimum path, avoiding the "count-to-infinity" problem that frequently occurs with distance-vector routing methods.

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11.5 Fisheye State Routing (FSR): FSR [44] is an enhanced form of GSR. In GSR, large update messages consume a significant amount of network bandwidth. FSR addresses this issue by delivering information about neighboring nodes more frequently, rather than including all nodes.

This decreases the size of update messages. Nodes will contain precise information about adjacent nodes, but the accuracy reduces as the distance between them rises. Even if remote nodes do not have the most exact information, the routing will remain proper since the path grows more accurate as it approaches the destination.

11.6 Ad Hoc On-Demand Distance Vector Routing (AODV): AODV [36,45,46] differs from previous distance-vector routing methods in its approach. AODV does not always preserve a routing table. Instead, it generates the routing table only when necessary. When a node wants to communicate data to another node, it sends out a Route Request (RREQ) packet [47].

- The RREQ packet contains information about the source of the request and the destination it attempts to reach.
- The RREQ is flooded over the network, with each node processing it only once to avoid loops. As the RREQ moves across the network, it generates a temporary record along the way.

When the destination node receives the RREQ, it determines the shortest path and returns a Route Reply (RREP) to the source.

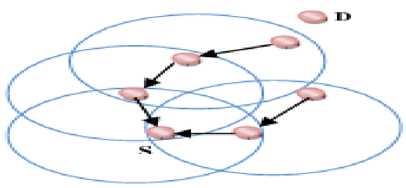

Fig 6. AODV: Reverse Path Formation

As the RREP travels along this path, it collects critical data. When the RREP is issued in response to the source's original RREQ, a segment of the path between the source and the destination is established. Following that, the source can utilize this route to transmit packets to the destination. It is worth noting that both AODV and DSDV routing tables include a destination sequence number. This helps to avoid routing loops and guarantees that the recorded path is always up to date.

IX. CONCLUSION

Mobile Ad Hoc Networks (MANETs) are a novel form of wireless communication that does not require a fixed infrastructure. They are adaptable and can change as the devices move. MANETs, unlike ordinary networks, require specialized routing algorithms to accommodate their ever-changing topology, limited bandwidth, energy consumption, and security concerns. This study examines over 13 different routing strategies, highlighting their pros and cons. It also demonstrates how MANETs are employed in a variety of fields, including military operations, disaster response, smart vehicles, and modern technologies. The report emphasizes the importance of MANETs in overcoming existing communication difficulties while also mentioning ongoing obstacles such as managing huge networks, saving energy, and maintaining network security.

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